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Study of the Small:
Potential for Operational Military Use of CubeSats

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ABSTRACT

The DoD is known for looking to innovative thinking to provide answers to it warfighter's needs. This holds very true in the realm of space based capabilities. Recently, the sizes of assets in space have been shrinking in size. However, their capabilities have been growing at an accelerated rate. CubeSats are quickly becoming an area of interest because of their growing potential to fulfill operational military missions.

Over the last decade or so satellites, like many other technologies, have been shrinking in size. Though their physical size is being reduced, the opposite is true for their capabilities. The increased fidelity of the bus architectures and payloads available today are allowing the small satellites to step out of the realm of research and development (R&D) and into the realm of the military's operational arena. The purpose of this research paper is to show the increasing potential for the use of these small satellites, particularly CubeSats, to fulfill the military's operational mission requirements.

Small satellites have been put into a class of their own. They are categorized based on their weight. The following table (table 1) shows the satellite classes[18]:

Table 1: Satellites bv Mass

Group Name	Wet Mass	
Large satellite	>1000kg	
Medium sized satellite	500-1000kg	
Mini satellite	**100-500kg**	**Small Satellites**
Micro satellite	**10-100kg**	
Nano satellite	**1-10kg**	
Pico satellite	**0.1-1kg**	
Femto satellite	**<100g**	

This paper will focus on CubeSats which fall into the nano and pico satellite categories.

A CubeSat is defined as 10 cm x 10 cm x 10 cm (Figure 1)[4]. This is considered the base unit and is referred to as a 1U. Multiple organizations have found they can fly useful missions with CubeSats larger than the base unit. A 3U is a very common form factor used by developers requiring 1.5U and 2U CubeSats. The size of the CubeSat also lends to the price of integration and availability of launch. The size of the CubeSat is usually determined by the needs of the mission. Typically, the larger the CubeSat the higher the weight and power (SWaP).

Figure 1: 3U and 1U Frame

CubeSats have been built by universities for some time because of their relatively low development cost. It is only recently that there has been an interest in incorporating small satellites into the inventory of the Department of Defense (DoD). These have been mostly R&D satellites, but now there is an increasing trend to move some of these satellites into an operational role.

To better understand how this booming growth of interest in CubeSats came about it is necessary to cover the history of the California Polytechnic State University (Cal-Poly) CubeSat Project[5]. The CubeSat Project was started in 1999 with the premise that creating a standard form factor for pico-satellites would allow for universities to move their spacecraft projects from the test stand to space for a relatively low cost. Their mission statement reads, "The CubeSat program strives to provide practical, reliable, and cost-effective launch opportunities for small satellites and their payloads.[5]" To facilitate this, a "CubeSat Standard" was published. This was an effort led by Cal-Poly aerospace engineering professor Dr. Jordi Puig-Suari with the collaboration of Bob Twiggs. Bob Twiggs is currently a professor at Morehead State University, and was a professor at Stanford University at the time.

The CubeSat standard is twofold as it pertains to the satellites, CubeSats, and their launcher, the Poly-Picosatellite Orbital Deployer (P-POD). The CubeSat and the P-POD drove the requirements for each other through their development. The following is the published CubeSat Design Specification:

"The CubeSat Standard states that a single CubeSat should be a 10-cm cube, and have a total mass of no more than 1 kg. The … specifications were derived from four basic sources:

1. The size of available commercial off-the-shelf (COTS) components …
2. The P-POD's dimensions and features
3. Launch vehicle environmental and operational requirements
4. Self-imposed safety standards"

This standard has made it easier for universities, and now industry and the military, to develop low cost satellites that have a better chance for being matched to a launch opportunity. There are various organizations outside of academia that are strongly promoting this standard. These organizations are discussed later in detail.

The second piece of the CubeSat Standard is the P-POD which contains and deploys the CubeSats. The design of the P-POD was a collaborative effort between Cal-Poly and the Space Systems Development Laboratory (SSDL) at Stanford University. The P-POD is a simple, yet effective, design. It is so simple that; it is sometimes referred to as a jack in-the-box. (Figure2)[5]. This simple design helps ensure an easy integration to the launch vehicle well as reliable deployment of the CubeSats.

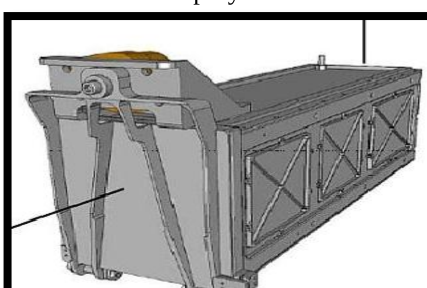

Figure 2: PPOD

"The P-POD was developed with seven primary goals:

1. Protect the primary payload

2. Protect the launch vehicle
3. Protect the CubeSats
4. Safely group multiple CubeSats for launch
5. Eject CubeSats for safe deployment
6. Increase access to space for CubeSats
7. Provide a standard interface to launch vehicles"[5]

These self-imposed safety standards help give the primary payloads and launch vehicle provider's piece of mind that their equipment will not be harmed. Despite these standards, each launch mission may still require significant mission unique testing. Depending on the launch vehicle the testing regime can be quite intense. The requirement for a mission unique test regime is a practice which the CubeSat community would like to change.

Cal-Poly is leading the charge to change the thinking of the space community which seems to be stuck the in the "big space" way of doing things. Currently, missions are planned and payloads are chosen years in advance of a launch. With the space community, especially the DoD, promoting the "responsive space," the current approach seems to be contrary to the goals of the community as a whole. The goal of the CubeSat community is to easily manifest any CubeSat that meets the CubeSat standard late in the LV manifest process. This is great for university satellites, but may become more of challenge when the CubeSat has to meet operational requirements. This challenge is discussed later in the paper.

The current model, shown in figure 3A , shows spacecraft are matched directly to a specific launch opportunity.[9] As mentioned in the previous paragraph, this matching can take place years ahead of the launch. This may be necessary for primary payloads which drive various factors of the launch like orbit and launch vehicle requirements. However, this is not true of P-PODs, which are normally considered a tertiary payload. P-PODs do not drive requirements for launches, they conform to them. This is why the CubeSat community is pushing to work via a new system for matching CubeSats to launch opportunities.

The Cal-Poly vision, shown in figure 3B, is that of flexible secondary launches.[9] Many CubeSat developers, all following the Cal-Poly standard and services, then are pooled together awaiting a launch opportunities. The idea is simple; when a launch opportunity is identified the CubeSat(s) that can live with the orbit, and are ready, get a ride. Everyone else waits for the next opportunity. In theory the CubeSat standard allows for last minute swaps of CubeSats. This is ideal, to ensure limited launch opportunities aren't wasted if a CubeSat has a failure in testing or can't be ready for launch in time for some other reason.

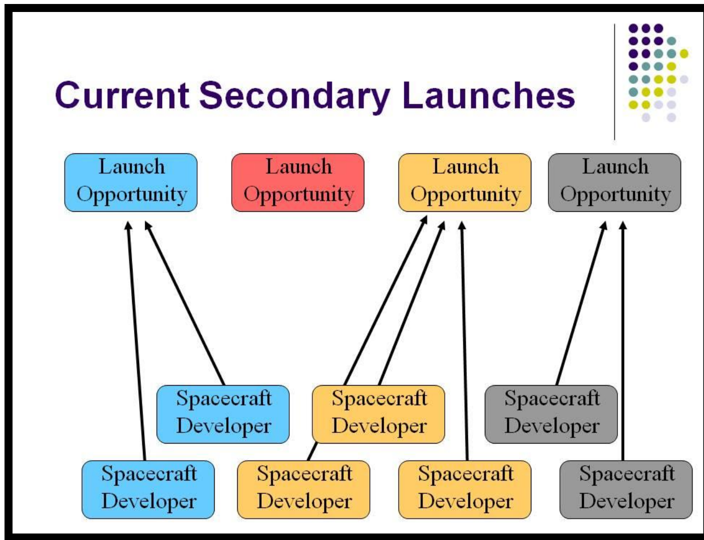

Figure 3A: Current Secondary Launch Model

This theory has been tested and was successful for a group of CubeSats on a Russian launch vehicle in 2006. This was due in part to the Russian LV treating the P-POD as a "black box" with standard interfaces. The LV didn't care what was in the box as long as it fit the CubeSat Standard. This approach has yet to be demonstrated on a U.S. launch vehicle. Due primarily to higher cost and lower risk tolerance, the process for U.S. launch vehicles has been much stricter and there is significantly more testing and paperwork involved.

There have been more than ten CubeSat missions to date. Many of the missions have been university-sponsored, some industry-sponsored, and a couple sponsored by NASA. These missions covered a wide range of applications from technology demonstrations to on-orbit biological testing. The diversity of applications already demonstrated is a testament to the flexibility of the CubeSat form factor. In order to better visualize CubeSats potential for operational military applications a review of the current CubeSat applications must be made.

Universities worldwide have succeeded in building and launching CubeSats. The first successful launch of university CubeSats occurred on June 30, 2003. There were six CubeSats manifested on the mission representing six separate universities from four different countries. The missions were as varied as the participants[15]:

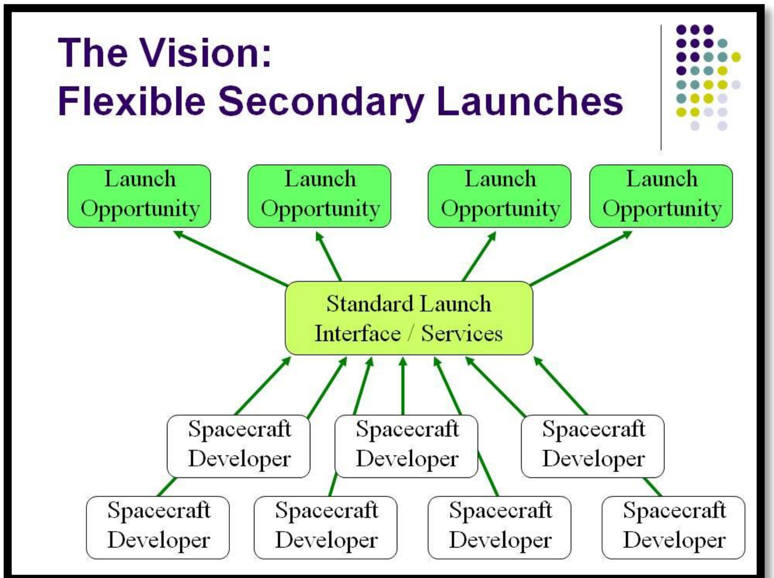

Figure 3B: Potential Future Secondary Launch Model

1. **CUTE-1**: Tokyo Institute of Technology, Japan; COTS components test bed
2. **XI-IV**: University of Tokyo, Japan; COTS components test bed; earth imaging camera
3. **CanX-1**: University of Toronto, Canada; space-testing key technology; star-tracker, GPS receiver
4. **AAU CubeSat**: Alborg University, Denmark; color CMOS camera
5. **DTUsat**: Technical University of Denmark: MEMS subs sensor, 600m tether for orbit change
6. **Quakesat**: Stanford University, USA: Detect ELF radio emission of seismic activity during earthquakes

Since the beginning of the CubeSat project, the participant list has grown significantly with a current count of over 250 organizations worldwide.

One well known participating organization is the NASA Ames Research Center located in San Jose, California. They are strong advocates of the CubeSat and the "Cal-Poly Standard." They have successfully built and launched two CubeSats with advanced scientific instruments for studying the effects of the space environment on biological entities. They have built a third CubeSat that is currently on the shelf waiting for launch next year on the Department of Defense (DoD) Space Test Program (STP)-S26 mission. NASA Ames is a leader in expanding the capabilities of a CubeSat bus. Many organizations contemplating CubeSat projects of their own have researched using the NASA Ames bus.

July 26th, 2006 saw another group of CubeSats launched out of Baikonur on a DNEPR launch vehicle. Unfortunately, the LV failed and all payloads were lost. Among the 14 CubeSats which were manifested on this mission was the NCube1, a Norwegian University Satellite. Unlike most CubeSats up to this point, NCube1 had a specific operational mission. NCube1 was to transmit maritime identification and position data of large vessels which it received from their Automatic Identification System (AIS). Along with tracking large vessels, NCube1 also has the unique task of transmitting similar information that it received from reindeer collars. NCube1's predecessor, NCube2, (don't be confused by the numbering, NCube2 was the first mission) was deployed from the SSETI Express satellite launched two years earlier, but radio contact was never established with NCube2.

Those are just a few examples of the various applications that have been undertaken by CubeSats that have been, or are currently, on-orbit. Although most CubeSats are used for the purpose of experimentation and technology demonstrations, there is a push to make them more operationally capable. In order for this to happen the two main pieces of the CubeSat architecture, the bus and the payload, must be enhanced. These enhancements will bring the CubeSat from being primarily a university student experiment to an operationally useful option for industry and the military.

Specific requirements for development of a CubeSat that adheres to the Cal-Poly standard are easily accessed via the CubeSat project website. These requirements cover materials and operational standards that ensure the CubeSat fulfills all the necessary safety procedures. The actual CubeSat structure is not where the bus needs enhancing. Like most other satellites the enhancements come with successfully balancing the (size, weight, and power) SWaP of the bus.

When it comes to CubeSats, the limited on-orbit power available for payloads is the most common complaint among potential military and industry users. The bus size and weight must conform to the Cal-Poly standard, but there is a pressing need to increase the power the bus generates. Currently, there are several private companies and DoD labs which are working to develop high efficiency solar panels that will generate substantially more power. On the CubeSat front specifically, the push is to move from the traditional body mounted solar panels to deployable and articulated solar arrays. The challenge is getting it all stuffed into the small package of the P-POD. There have been a few CubeSats which have successfully used deployable solar panels which deploy to a fixed angle and stop. Those panels have been only as large as the surface area of a single CubeSat side. Surface area is king when it comes to solar cells.

Keeping that rule in mind, two organizations are trying to put big things into small packages. The Air Force Research Laboratory (AFRL) and a private small business venture are working to develop deployable and articulated solar arrays with a large surface area for CubeSats. (Figure 4) The goal is to provide over 20 watts of on-orbit average power which is four to five times greater than what the current CubeSat solar arrays can offer. With the incorporation of high efficiency solar cells, the on-orbit average power may be increased even more. If these solar arrays perform as expected it will enable enhancements to other areas of the bus.

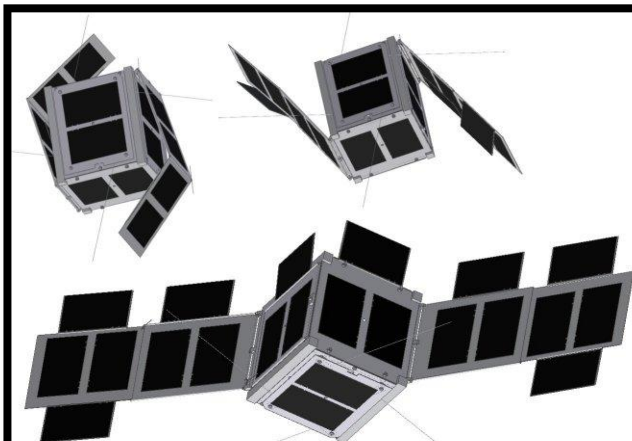

Figure 4: Deployable CubeSat Solar Arrays

The second bus feature which is on the minds of industry and the military is the Attitude Determination and Control Subsystem (ADCS). This subsystem has been a challenging area for CubeSats, again due to the SWaP requirements. In order to be effective for operational missions the ADCS should provide high accuracy pointing and determination. Most early CubeSats were tumblers. They just ride the earth's magnetic field with no real pointing control. As time passed, developers began using simple magnetorquers and gravity gradient booms to keep the satellite pointed in the desired direction. Today, there are many options for CubeSat ADCS including newly developed miniature reaction wheels. Increasing bus capability and keeping the subsystems small will allow for the integration of the technologically advanced payloads needed for operational missions.

Many in industry are hearing these needs and are working to answer the call. One organization in particular has a keen ear for the needs of the CubeSat community. That organization is Utah State University's Space Dynamics Lab (SDL). As host of the summer CubeSat workshop and the annual Small Satellites Conference (Small Sats), SDL are be considered experts on the subject of small satellites. They recognize that in order to move CubeSats to the operational realm they will need a bus that will support stringent mission requirements. This is a move away from the original Cal-Poly philosophy of using a majority of COTS parts for the CubeSat. In a brief at the Small Satellites Conference SDL introduced their approach for building CubeSats designed to support operational missions. "The SDL approach (is to) follow the CubeSat standard (because) it is still very effective. (Then), incorporate the reliability, parts quality, performance, and design rigor required of high-profile, operational missions."

With the introduction of this new approach, SDL also revealed its CubeSat architecture, the PEARL bus (Figure 5)[14]. The PEARL bus is a 3U CubeSat which incorporates the top-of-the-line in CubeSat subsystem technologies. The bus features four deployable solar arrays as well as four fixed, body-mounted panels. SDL has developed mini-reaction wheels for pointing that take up only 0.5U. In conjunction with the miniature reaction wheels is a miniature sun-sensor which has a targeted accuracy of 0.01 degrees. The avionics chassis takes up 1.5U which leaves 1U available for the CubeSat payload. This capable bus was developed with the needs of the military in mind, as its development was sponsored by AFRL, Kirtland AFB, NM.

CubeSat payloads have run the gamut from simple university experiments like an RF beacon to sophisticated biological testing equipment.

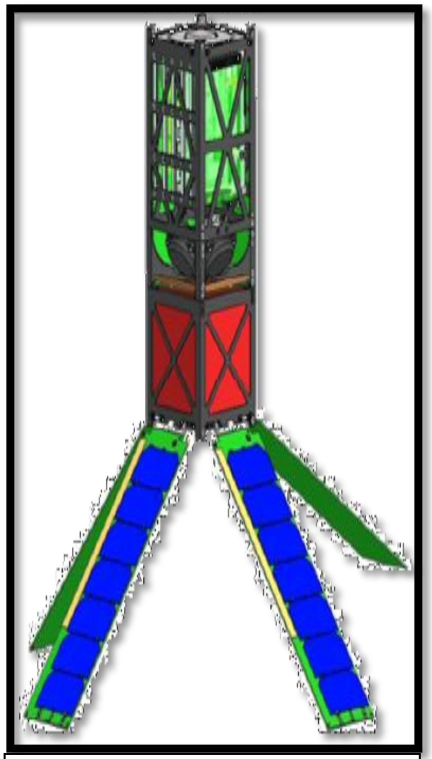

Figure 5: PEARL Bus

Organizations are continually miniaturizing and maturing technologies specifically for use in the CubeSat form factor. This process is not cheap. However, transitioning a payload to fit the CubeSat form factor may give the mission a better chance of getting to space for a lower cost in a shorter time frame than if it stayed a larger size.

One example of resizing to the CubeSat form factor in order to gain a better chance at a space flight opportunity is a Space Experiments Review Board (SERB) experiment, the Polar Orbiting Passive Atmospheric Calibration Spheres (POPACS). Primary Investigator (PI), Gil Moore, has been briefing the POPACS experiment at the SERB for three years. Although the experiment goals remain the same the packaging of the experiment has evolved over those years. Originally, the POPACS design consisted of a single 10kg sphere with a volume of 524 cubic centimeters. The original sphere was deployed by what Mr. Moore called a heavy duty P-POD. As the Cal-Poly standard became accepted as "The CubeSat standard" by those in industry and the DoD, it was suggested that Mr. Moore redesign POPACS to fit to that standard.

Mr. Moore took that advice and came to the 2009 SERB with a totally redesigned POPACS experiment. He restructured the POPACS experiment to the Cal-Poly standard making it a 3U CubeSat. The design calls for a 2U bus with the calibration sphere filling the remaining 1U. The POPACS CubeSat bus development follows a new design method using rapid prototyping. This design may require a waiver since it is outside the normal structural materials requirements set forth by Cal-Poly. However if the design proves successful, it will cut bus structure development time dramatically and may cut costs as well. These two development aspects drove the initial idea behind the Cal-Poly CubeSat project.

Mr. Moore's design also calls for a low pressure propulsion system which will allow the CubeSat to increase the eccentricity of its orbit. Since the CubeSat is able to change orbits it allows the experiment to be more easily matched to launch opportunities because the orbit is less of a restrictive factor. The propulsion system designed for the POPACS CubeSat has the potential for use on future CubeSats with operational missions. Other CubeSat developers are also working on propulsive systems for CubeSats.

It is becoming obvious that the CubeSat form factor is quickly becoming the way of the future for small satellites. However, there is still a heated debate over the actual operational usefulness of a CubeSat is. Following the Chinese A-Sat demonstration and the collision of a dead Russian COSMOS satellite with the Iridium communication satellite the concern about space debris has been a hot topic of discussion among many in the space community. There are some in the space community that believe that CubeSats, due to their short operational lifetimes and increasing numbers will worsen the space debris problem.

Early in the CubeSat project this was not a large concern as many of the CubeSats were put into very low earth orbits and burned in relatively quickly. As the number of CubeSat developers grew a question that arose: If I can do a little science with one CubeSat, how much can I do with two, or three, or more? Now there are a few proposed projects which hope to fly a "cluster" of CubeSats. The idea of a large number of CubeSats deploying into low earth orbit at one time, to some, is like laying a mine field in space.

Despite the nay-saying from some members of the space community, others are pushing ahead with plans for large scale multiple CubeSat missions. One such organization is the National Reconnaissance Office (NRO), which is planning two separate multiple CubeSat missions; Colony I and Colony II. These missions are set up to leverage multiple CubeSats which will carry various Space Environmental Monitoring (SEM) payloads. The idea is that a cluster of CubeSats with various sensors orbiting at the same time will build a more complete picture of the space weather environment. This is important to the NRO because the information gathered may be added to current space weather outage prediction models. These models, in turn, provide valuable data for the prediction of space weather events which may adversely impact the large national assets under control of the NRO. Although CubeSats are out of the normal purview of the NRO, the decision to pursue these missions shows that the NRO leadership has identified the great operational potential that they offer.

There is a similar international CubeSat effort, QB50, focused on creating "a … network of 50 CubeSats for multi-point, in-situ measurements in the lower thermosphere and re-entry research."[10] Headed by the von Karman Institute for Fluid Dynamics in Belgium, this project has gained support from the National Aeronautics and Space Agency (NASA) as well at the European Space Agency (ESA). This statement from the QB50 website clearly defines the need for a mission which utilizes multiple networked CubeSats:

"Up to now, about 40 CubeSats have been successfully launched; worldwide an estimated 70-100 CubeSats are being readied for launch in the next few years. A single CubeSat is simply too small to also carry sensors for significant scientific research. Hence, for the universities the main objective of developing, launching and operating a CubeSat is educational. However, when combining a large number of CubeSats with identical sensors into a network, in addition to the educational value, fundamental scientific questions can be addressed which are inaccessible otherwise."

The total CubeSat compliment is truly a worldwide collaboration with 36 CubeSats coming from 21 different countries in Europe, 10 provided by U.S. universities, and the remaining 4 coming from Canada and Japan. The QB50 project is quite an endeavor, and if successful; it will prove the increased utility of flying multiple CubeSats over a single CubeSat and help demonstrate CubeSats aren't just space debris.

In order to discuss the potential military utility of CubeSats the doctrine which guides military space operations must be reviewed. The doctrine sets the standards and needs against which the operational utility of a CubeSat mission can be judged. The potential for operational military use of CubeSats may be rated by the quality of contributions a CubeSat mission can make toward achieving the end goals set forth by the doctrine. For the purpose of this research paper the Air Force's doctrinal documents, AFDD 2-2 Space Operations and AFDD 2-2.1 Counterpace Operations, are reviewed.[16&17]

AFDD 2-2, Space Operations, covers Air Force space operations in its entirety. This is a rather short document at only 31 pages and 6 chapters when compared to its counterpart AFDD 2-1, Air Warfare, a 118 page document. AFDD 2-2 outlines several areas in which the military utility of a CubeSat mission can be proved or disproved. In order to make this review the following questions need answering:

1. Can the mission be categorized under one of the following categories: Space Control, Application of Force, Enhancing Operations, or Supporting Space Forces?
2. Does the mission follow any of the "Attributes of Space Power"?
3. Can the mission be included in any of the "Space Employment Concepts"?
4. Can the mission fulfill any of the "Notional Space Power Capabilities"?

If the CubeSat mission can answer affirmative to any of the above questions, then there is some military utility in the mission. The easiest way to complete this mission comparison is to match CubeSat mission capabilities against the capabilities listed in Appendix A of AFDD 2-2, Notional Space Power Capabilities.

AFDD 2-2.1, Counterpace Operations, provides an in-depth look at key aspects of Air Force space operations. It is through this document which the operational utility of a CubeSat mission can be measured. This can also be measured in part against the guidance provided in AFDD 2-2. However to get a complete picture of the quality and quantity of operational military utility the CubeSat provides, its mission must be reviewed in comparison to the contents of both documents. AFDD 2-2.1 provides specific examples of space operations and their goals.

For instance, the section on Space Situational Awareness (SSA) states:

"SSA involves characterizing, as completely as possible, the space capabilities operating within the terrestrial and space environments. SSA information enables defensive and offensive counterspace operations and forms the foundation for all space activities. (An example of SSA is) improving the commander's situational awareness and view of the battlespace. Find, fix, track, target, engage, and assess space capabilities."

If a CubeSat mission can accomplish one or all of the above mentioned goals, then it should be considered an operational use of a CubeSat fulfilling or augmenting an operational need. The higher the quality of the information the CubeSat provides, the more operationally relevant it is. The same can be said for the quantity of information provided or the number or capabilities the satellite offers.

Today, there are CubeSats missions on-orbit, and many waiting to get there which provide some degree of military utility. A number of CubeSats have brief and been ranked by the SERB in hopes of being matched to a space flight opportunity. In order to be ranked by the SERB, the experimenter must show there is a military relevance to the mission. The military relevance category is 60% of the SERB composite score. The scoring at the SERB is completed by a panel of experts representing the military, DoD labs, and NASA. The CubeSats on the SERB list demonstrate that at least some DoD experts see a military utility to CubeSats, the SERB process is reserved for those who are conducting a strictly experimental mission. Thus, no SERB CubeSats, or any other SERB experiments, are used in an operational role.

In order to better understand the potential for CubeSats to fill an operational military role, the Air Force has ordered studies be conducted which explore the subject in depth. Once such study conducted by the NRO led to their Q_bX initiative.[1] Q_bX lead, Pat Bournes, gave an eye-opening brief at the 2009 CubeSat conference at Cal-Poly in April. Mr. Bournes described a CubeSat revolution and implied that it is quickly becoming the new space race. The concern is that the international community is pressing ahead quickly with maturing CubeSat technologies and that the U.S. may be falling behind. The Q_bX program is striving to show that CubeSats will become operationally useful to the military in the near future if given the needed attention. To ensure this, Q_bX is funding multiple projects that should increase the potential for operational usefulness of CubeSats. Some of these initiatives are:

- Hyperspectral Imagers
- 19db Deployable Antenna
- Plug and Play (PnP) Attitude Control
- Structureless Antenna
- Rate Adaptable, Constant Power Downlinks
- H-1 Beacon and UHF/VHF Radio
- Module

He called the CubeSat standard "containerization of space." He believes that with the P-POD and its enablers, the CubeSat will create a paradigm shift from the large, long-lead time satellites to the small responsive CubeSat. This shift will allow CubeSats to fill or augment operational military missions at a moment's notice.

The Air Force has called for some of its other contractor support to make in depth investigations and reports on the potential future uses of CubeSats. Some of the studies are multiple volumes in length and cover a great deal of uses for future CubeSat missions. However, due to the proprietary nature of the studies, the information may not be used for reference in this paper. The fact these studies were ordered shows the military does have an increased awareness of the potential for CubeSats to be used in an operational role.

Despite the great interest the Air Force shows in the research and possible development of an operational military CubeSat, it appears that the Army has beaten them to the punch. At the same CubeSat conference during which Pat Bournes introduced the NRO's Q_bX program the U.S. Army Space and Missile Defense Command (SMDC) unveiled what could prove to be the first operational military CubeSat, SMDC-ONE. The ONE in SMDC-ONE stands for Operational Nanosatellite Effect. On April 29, 2009 the Army took delivery of eight SMDC-ONE CubeSats.

The SMDC-ONE CubeSat has four main mission objectives. Those objectives were briefed as follows:[13]

1. Demonstrate the ability to rapidly design and develop military relevant low cost space craft.
2. Primary Operational Objective: Scenario OV-1. Received packetized data from multiple Unattended Ground Sensors (UGS). Transmit that data to ground stations within the SMDC-ONE ground track.
3. Secondary Operational Objective: Scenario OV-2. Provide real time voice and text message data relay to and from field deployed tactical radio systems.
4. Demonstrate SMDC-ONE operational life time of 12 months or longer.

They have completed their first objective with the delivery of the eight SMDC-ONE CubeSats (Figure 6).[11] The entire design, development, and delivery took place in less than one year from start-up. The cost was also relatively low at less than $400k per spacecraft delivered. It is just that kind of responsive acquisition that will make CubeSats a more viable option in the future.

The SMDC-ONE fact sheet sums up how CubeSats can be used in the future for operational military missions.

"Nanosats deployed in large numbers can provide enhanced capabilities over large latitudinal swaths of the earth or even globally. Because they are low cost, they can be "refreshed" frequently by launching replacements, which allows rapid technology upgrades, reduces the unit reliability requirements,

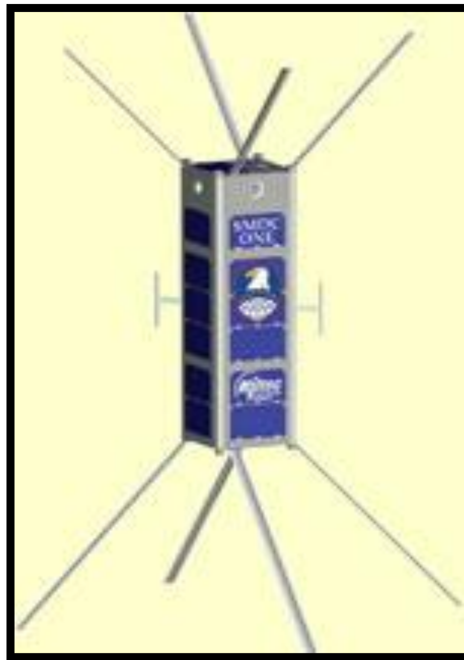

Figure 6: SMDC 1

and allows for manufacturing economies of scale. A nanosat constellation populated by inexpensive spacecraft could be useful in tactical ground operations, humanitarian support, and stability operations. If some satellites are lost, they can be rapidly reconstituted. They can provide coverage over specific regions as well as globally. The use of nanosats in such fashion will enable UAV like performance for communication from space-borne assets that can provide data directly into theaters of operation."

The initial success of SMDC-ONE's acquisition and development has led the Army to pursue various other CubeSat and Nanosat projects. However, SMDC-ONE has also highlighted the continuing issue of CubeSat launch opportunities since it has yet to find launches for the eight spacecraft.

One SMDC program that promises to make an impact on the small satellite community is Kestrel Eye. Although not a CubeSat, Kestrel Eye is a nanosat, weighing in at only 9.5kg. This nanosat is an imager which will provide the warfighter in the field unprecedented access to satellite imagery. The first iteration is a single satellite tech demo. The follow on plan is to orbit a small constellation of approximately thirty satellites to provide persistent theater coverage. As technologies mature this capability may be repackaged to fit the CubeSat form factor and be fielded as a fully operational system.

Space and Missile System Center (SMC) has also joined the ranks of CubeSat developers. SMC is the Air Force organization responsible for contracting the most recent study of the viability of CubeSats for operational missions. This study has led SMC to publish a request for information from industry regarding the use of CubeSats to fulfill a SEM mission. This interest in using CubeSats to fulfill SEM missions grew as a result of the availability of sensors which were de-manifested from the National Polar-orbiting Operational Environmental Satellite System (NPOESS) mission and the need to fill the capability gap left by that action.

In order to fill this identified capability gap SMC plans to acquire two CubeSats from a company that is yet to be determined. There are several payload options that have been identified at this time which are able to meet the requirements set forth by the Defense Meteorological System Group. Some of the payloads identified by SMC have briefed the SERB and have a significant military relevance.

The SEM mission seems to be very popular for CubeSats because the sensors are relatively small and the science they collect is very useful. There are several other initiatives which have identified CubeSats as a viable asset for flying SEM payloads. These initiatives are the NRO's Colony I and II program, the National Science Foundation's (NSF) National Space Weather Program (NSWP), and the International QB50 project. The data returned from all these programs will contribute to various models that will help gain a better understanding of how the space environment affects on-orbit assets, both military and civilian.

The previous sections of this paper provided background information describing what CubeSats are and how they are currently being used today by universities, industry, and the military. The next appropriate action is to look to what the future holds for CubeSats. For the purpose of this paper, the focus is on the use of CubeSats as a military asset. As mentioned before the Air Force has contracted studies that point to some of the future capabilities of CubeSats. However, the information in the studies doesn't focus on solely military applications. Also, the timelines for CubeSat technology development are quite conservative. For instance, the study shows some of the capabilities are expected to be available for ten years. In reality, those capabilities will be ready in 12 to 24 months from today. The CubeSat has a great potential for operational military use and shouldn't be discounted as a simple university project or, as some say, space debris.

In order to better describe how CubeSats may be used for future military missions, examples are shown for the following mission areas: Intelligence, Surveillance, and Reconnaissance (ISR), Communications (COMM.), Space Environmental Monitoring (SEM), Space Situational Awareness (SSA), and others. These mission areas were chosen based on content of the CubeSat studies provided to various Air Force organizations. For some of the examples to be viable as real military missions, changes in space doctrine and or policy must take place.

ISR is a pivotal military mission area. The gathering and exploitation of information gathered via various methods has been a cornerstone in military strategic planning for centuries. First, there were scouts on foot. Then came balloons, aircraft, satellites, and unmanned aerial systems (UAS). All of these methods have been, or are currently, employed by a commander to get a "picture" of the battlespace. The current operations in Iraq and Afghanistan have pushed ISR capabilities to their limit.

There is just not enough access to ISR assets to fulfill everyone's needs. The problem doesn't lie, necessarily, in the amount of assets available. There are multitudes of aircraft, UAS, and national assets available to the battlefield commanders to task. However, there is a priority for the use of those assets and some units which are in dire need of immediate intelligence may not be at the top of the list. When the information does come down it may not filter to the small unit leaders at the lower level who are actually executing the mission. If it does filter down to the small unit leader, it may be well over 24 hrs old. Time is critical when it comes to gathering and exploiting intelligence-nothing spoils faster.

CubeSats may be the answer for providing ISR assets which are responsive and have the ability to be tasked by lower echelon units. Currently, there are several earth-imaging CubeSats in development which are ideal for filling the ISR mission. The challenge for CubeSats in filling an ISR role is the quality of images. The trade-off which must be made is quality versus availability. For a small unit commander, an image that has a 1.5 to 3 meters resolution provided in 1 hour to 30 minutes is more useful than a higher resolution image that is much older.

The Tactical Imaging Nanosat Yielding Small Cost Operations Persistent Earth coverage (TINYSCOPE)[19] is a SERB experiment being developed by the students at the Naval Post Graduate School (NPS). The objective of TINYSCOPE is "… to demonstrate the capability to obtain multiple ~3.5 (ground swath distance) GSD images and send them to the ground during a single orbital passage, for tactical and natural disaster response applications." The concept of operations for TINYSCOPE involves allowing troops on the ground access to a Virtual Mission Operations Center (VMOC) giving them the ability to submit tasking requests from the field. The requests flow via Secure Internet Protocol Router Network (SIPRNET) to an in theater satellite ground terminal which has control of the satellite. Once the information is received by the ground station it is immediately sent back to the requesting unit.

Given a constellation of sixty three satellites, the warfighter would be provided with near persistent global coverage. Average revisit times are predicted to be 30-40 minutes anywhere on the globe. With this persistence and the capability to task locally, small unit commanders would be given on-call intelligence which will greatly enhance the effectiveness of their mission and the safety of their troops. As technology matures, the addition of multispectral imaging, hyperspectral imaging, and full motion video will be added to CubeSat payloads making them an indispensable asset to the small unit commander.

Another vital military mission tasked to today's satellites is communications. Without working communications an entire Army can be halted, missions scrubbed, or worse. Although there are many military communication satellites providing almost global coverage, there is still the possibility of outages or dead zones. CubeSats can fill coverage gaps and act as a responsive temporary comsat replacement in the event of an outage. As mentioned in earlier sections of the paper, the first operational military CubeSat will most likely fill a communication and data exfiltration mission (SMDC-ONE).

There is a growing possibility of communications satellites being destroyed or disabled. The recent collision between an Iridium communications satellite and the defunct Russian COSMOS satellite is proof of that. In the future the destruction or disruption of military communications satellites may not be accidental, but intentional. The short development time and responsive launch options afforded to CubeSats because of their ease of integration make them the ideal gap filler in the event of such an incident. The incorporation of high data rate transmission, software and hardware encryption, and crosslink capability (all which are currently in development), will make the CubeSat the obvious choice to accomplish the mission.

SEM is another important military mission with a basis in science and meteorology. According to AFDD 2-2.1, Counterspace Operations, environmental operations includes the following:

"The characterization and assessment of space weather (i.e. solar conditions) on satellites links, terrestrial weather near important ground nodes, and natural and man-made phenomena in outer space (i.e. orbital debris). The environmental information must be accurate, timely, and predictive to protect space systems and to support counterspace planning and execution. Predictions of natural environmental effects should be synchronized with military commanders' courses of action to enhance military effects. … Operators must be able to differentiate between natural phenomena interference and an intentional attack on a space system in order to formulate an appropriate response."

AFDD 2-2.1 is primarily concerned with the current state and effects of the space environment. Analysis of the data provided by SEM sensors provides the ability to predict outages of important military systems like the Global Positioning System (GPS) and Military Satellite Communications (MilSatCom). This information is crucial for military commanders when planning battlefield engagements.

The SEM mission area also includes detailed monitoring of the terrestrial environment as well. This is not limited to basic meteorology, but is also concerned with oceanography, topography, and hydrology. Data gathered from all these areas are crucial in planning a successful military operation. Currently, there are several space-based systems which collect such information. Most are large "Battlestar Gallatica" satellites with a multitude of sensors which take many years and many millions of dollars to develop. This can lead to gaps in data collection as the aging satellite systems are decommissioned or fail while waiting for the development or launch of a replacement. In the future, the interruptions or failures may be a result of an intentional denial, disruption, or destruction, of the system by an enemy force. There must be a low cost, responsive capability which can supplement the data gathering of the lost asset. CubeSats could be the answer.

Small satellites may never permanently replace the larger SEM satellites because of the sheer amount of information they provide and the large area of earth in which their sensors cover. However, CubeSats could be used as a gap-filler because of their low cost and short development time. Many SEM CubeSats are already in development and some are on-orbit. There are also various military and international efforts pursuing the development of SEM CubeSats, as described earlier in the paper.

Most recently, the NSF has been given funding through their NSWP to develop, build, and launch multiple SEM CubeSats. The first of which is scheduled to launch in mid 2010 on the STP-S26 mission. The bus is being built by the students of the University of Michigan in collaboration with NASA Wallops. The payload has been developed by the Stanford Research Institute (SRI). The Radio Aurora Explorer (RAX) seeks to gather data on scintillations caused by various reactions in the ionosphere.[6] It is theorized that scintillations such as these contribute or cause interruptions and outages of space assets. The data returned will be most valuable as it is added to the knowledge base from which various prediction models are developed.

CubeSats are well suited to augment the SEM mission area in the future. Combined with the development of CubeSat launch enablers and dedicated small launch vehicles, getting needed assets into orbit in a responsive manner in order to fill gaps in coverage will be easily accomplished. This will ensure combatant commanders aren't without vitally needed information no matter what happens with the current on-orbit assets, whether the loss of that asset is natural or intentional.

SSA is a mission area of growing importance to the military, the Air Force in particular. According to AFDD 2-2, ISR and SEM both fall under the heading of SSA. The goal of this section is to highlight the "R" in ISR as it pertains to the reconnaissance of on-orbit objects, especially spacecraft acting in a suspect manner. Currently, characterization of on-orbit objects is accomplished by various terrestrial assets including, radars, lidars, and high-powered telescopes. The sites are located at various locations throughout the U.S. and the world. Many of these locations, Thule, Clear, Cavalier, and Fylingdales for example, were part of the Air Force's early warning system. Their primary missions have shifted from that of missile warning to SSA.

This was considered the best method of detecting, tracking, and characterizing on-orbit objects until earlier this year. An article released in January 2009 described a "top secret" operation in which two "covert inspection satellites" were used to inspect an Air Force Defense Support Program (DSP) satellite which had failed after only one year on-orbit. The inspection of the failed DSP (Figure 7) satellite was completed by two "Mitex" inspection spacecraft. Launched into a geosynchronous orbit in 2006 as part of a classified Defense Advanced Research Projects Agency (DARPA) experiment, the two satellites were tested by maneuvering around and inspecting each other. No information is available stating that they had previously inspected any other spacecraft in the GEO-belt before inspecting DSP 23.[2]

Figure 7: DSP Satillite

Spacecraft in the GEO-belt, which is an altitude of around 22,000 miles, are increasingly difficult to detect and track. The challenge is even greater if the objects are relatively small. This fact is part of the reason the Mitex satellites were able to maneuver freely while remaining undetected. The article points this out specifically, stating "one key feature aiding the Mitex spacecraft to fly undetected is they are unusually small, only about 500 pounds each." Their size may be a benefit, but it is also an inhibitor as it limits the amount of propellant available for maneuvering. That being said, the Mitex satellites that completed the inspection will be using the rest of their propellant to push themselves to a graveyard orbit.

Despite the upcoming retirement of the Mitex satellites, the Air Force will not go without space-based SSA assets in the future. There is ongoing research on the possibility of using nanosats and CubeSats in a similar role. A 2005 study of military space systems sponsored by MIT and the Institute for Defense and Disarmament Studies theorized this possibility for the use of CubeSats:[7]

"Imagine a host docking or mother satellite with multiple "CubeSats" loaded on board. Each would be no larger than 10 inches per side. These satellites could fly in formation, dock with other space assets, provide imaging and,… perform inspections of other satellites."

In order to avoid detection, the host satellite would "park" out of range of the detection capabilities of the target. The inspector satellites would deploy from the host, orbit the target, and then return to the host to download the data collected. The deployed CubeSats would remain covert because of their small size. CubeSats have proven the capability to image other spacecraft on-orbit. In these cases, it has been the satellite or spacecraft from which the CubeSat has deployed.

There are mission areas in AFDD 2-2 and 2-2.1 which are currently prohibited by current policies or treaties. However, these concepts must be examined because the geo-political climate is fluid, policies change, and treaties may be broken. The potential for warfare to expand to the realm of space is a real possibility. ASAT weapons have been successfully tested by the U.S. and other countries. There may come a time when the U.S. must defend its space assets through various offensive and defensive counterspace operations, some of which may use destructive means.

The impact of using weapons in space has been pondered since the first satellite was placed on-orbit and even before. The same study of military space systems sponsored by MIT and the Institute for Defense and Disarmament Studies also stated this possibility for the use of the previously mentioned inspector CubeSats:

"In theory, a CubeSat might, for example, place a black swath of adhesive material over a satellite lens or solar array, and then remove it once the objective (concealment of some activity) has been met. This is referred to as a "stealth" satellite attack, an attack that duplicates natural phenomenon or is reversible. Once this act is executed the CubeSat would return to the host satellite … recharge its batteries and transfer images or data collected."

This form of counterspace operation, since it is reversible, is considered denial, disruption, or degradation of an enemy system.

There is a possibility for using CubeSats to permanently destroy or disable an enemy space asset. Using the same concept of operations (conops) as described above, CubeSats could deploy from a host satellite and move toward the target. Once at the target the CubeSats, depending on the payload, could do several things. One option is very similar to the adhesive example mentioned previously. However in this case, the CubeSat would disable the sensors of the satellite by using paint. This is a simple step up from the previous example, just more permanent.

The following examples are destructive options for the use of a CubeSat as an ASAT. Both examples require the CubeSat to dock to the target satellite, which in theory they should be able to do since they may go back and dock with the host. The first option would be to use a CubeSat that has a large deployable solar sail incorporated as its payload. The CubeSat would attach to the target satellite, after which it would deploy the solar sail. This, in theory, would de-orbit the enemy satellite to a point that it burns in to the atmosphere. Depending on the orientation of the deployed solar sail, it may result in the shadowing of the target satellites solar cells or sensors. This would further degrade the target satellites capabilities.

The effectiveness of this measure is dependent on the size of the solar sail and the altitude of the target. Currently, there is a CubeSat based solar sail, NanoSail-D, which is manifested on the Fast, Affordable, Science and Technology Satellite (FASTSAT) on the STP-S26 mission. The purpose behind this experiment is to find out how fast the solar sail will de-orbit the satellite. The goal is to use the solar sails in the future to allow for orbital changes and to keep satellites within the 25 year de-orbit requirements. The initially peaceful purpose may be used to fulfill wartime objectives in the future.

The second example of a destructive ASAT mission a CubeSat may be designed to perform is that of a "space mine." A subject of many science fiction books and movies the space mine is essentially an explosive device on-orbit. Much like any other mine it may be designed to detonate on contact, in proximity, or by remote. Although, complete destruction of an enemy asset is usually deemed the most effective, it is not the preferred method for space. A space mine would be a last resort weapon because the amount of debris caused by the satellite destruction would create a risk for all other space assets. This has been proven by the debris fields created by the Chinese ASAT test and the collision of an Iridium satellite and a Russian COSMOS satellite.

The CubeSat has a great potential to augment, or even fulfill, many operational missions, both civil and military. The growing interest in CubeSats from the military and members of industry have accelerated the development of CubeSat technologies and CubeSat enablers. Many of these new technologies are already scheduled for upcoming launches and on-orbit tests. The CubeSat may be filling operational roles sooner than many have predicted.

REFERENCES

1. Bournes, Pat. "QBx." Keynote speech, Small Satellites from AIAA/Utah State University, Logan, Utah, August 10, 2009.

2. COVAULT, CRAIG. "Spaceflight Now | Breaking News | Secret inspection satellites boost space intelligence ops." Spaceflight Now. http://spaceflightnow.com/news/n0901/14dsp23 (accessed December 12, 2009).

3. Cayson, Stephen. "U.S. Army SMDC Space and Cyber Technology Directorate Overview." Lecture, SDTW Wing Involvement Meeting from SDTW, Kirtland AFB, NM, October 1, 2009.

4. PUMPKIN Inc.. "CubeSat Kit Home." CubeSat Kit Home. http://www.cubesatkit.com (accessed December 12, 2009).

5. Cal-Poly. "CubeSat in the News." CubeSat in the News. http://www.cubesat.org (accessed December 12, 2009).

6. Galliand, Chalie. "STP-S26 PRR#4." Lecture, STP-S26 Payload Readiness Review from Space Test Program, Kirtland AFB, NM, Sept 4, 2009.

7. Hoey, Matthew . "MILITARY SPACE SYSTEMS: THE ROAD AHEAD." Lecture, Symposium on Non-proliferation and Disarmament from MIT and the Institute for Defense and Disarmament Studies, Cambridge, MA, October 22, 2005.

8. "National Space Weather - Strategic Plan." OFCM Homepage. http://www.ofcm.gov/nswp-sp/text/a-cover.htm (accessed December 12, 2009).

9. Puig-Suari, Jordi. "CubeSat Launch and Development." Lecture, AFRL Meeting from AFRL, Kirtland AFB, NM, June 30, 2009.

10. Von Karmam Institute for Fluid Dynamics. "QB50." QB50. www.vki.ac.de/QB50/project.php (accessed December 9, 2009).

11. U.S. Army and SMDC. "SMDC-ONE." FactSheets. www.smdc.army.mil/factsheets/smdc-one.pdf (accessed December 9, 2009).

12. "Small Satellites." Small Satellites. centaur.sstl.co.uk (accessed December 9, 2009).

13. Weeks, Dave . "SMDC-ONE: An Army Nanosatellite Technology Demonstration." Lecture, Small Sats Conference from AIAA/Utah State University, Logan, Utah, August 12, 2009.

14. Young, Quinn . "PEARL CubeSat Bus Building Toward Operational Missions." Lecture, Small Satellites Conference from AIAA/Utah State University , Logan, Utah, August 8, 2009.

15. "denMike's tiny page." Micro Technological Corp. - Welcome. http://mtech.dk/thomsen/index.php (accessed December 12, 2009).

16. *Air Force Doctrinal Document 2-2.1: Counterspace Operations*. Maxwell AFB, AL: Air Force Doctrine Center, 2004.

17. *Air Force Doctrinal Document 2-2: Space Operations*. Maxwell AFB, AL: Air Force Doctrine Center, 1998.

18. Centaur. "Satellite Classification." Small Satellites Home Page. centaur.sstl.co.uk/SSHP/sshp_classify.html (accessed December 5, 2009).

19. Romano, Marcello. "Project TINYSCOPE." Lecture, SERB from Space Test Program, Washington DC, October 17, 2009.